Directional Collision Avoidance in Ad Hoc Networks

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Abstract— This paper analyzes the performance of directional collision avoidance schemes, in which antenna systems are used to direct the transmission and reception of control and data packets in channel access protocols based on four-way handshakes to try to avoid collisions. The first analytical model to consider directional reception and the possible difference in gain between omni-directional and directional transmissions is presented. Analytical results show that, when the directional collision avoidance scheme in which all transmissions are directional is augmented with directional receiving, one-hop throughput does not decrease due to the increased spatial reuse, even when the number of competing nodes within a region increases. It is also shown that, as expected, the performance of directional collision avoidance schemes degrades when directional transmissions have much higher gain than omni-directional transmissions. However, this degradation is relatively small. Simulations of the IEEE 802.11 protocol and its directional variants validate the results predicted in the analysis. The simulation results also show that the presence of broadcast traffic does not degrade the performance of the all-directional collision avoidance scheme significantly, even for relatively large percentages of broadcast traffic. The performance results of this study indicate that the most attractive collision avoidance approach consists of using directional transmissions of control and data packets, together with the directional reception of packets whenever a node is expecting a particular packet. Given the high tolerance to broadcast traffic of directional collision avoidance schemes, it is argued that the periodic transmission of beacons omni-directionally suffices to provide such schemes with the relative location of neighboring nodes.

Index Terms— Collision avoidance, ad hoc networks, IEEE 802.11, directional antennas, spatial reuse

I. INTRODUCTION

Collision avoidance is very important in ad hoc networks to combat the "hidden terminal" problem that can degrade throughput significantly. The usual four-way collision avoidance handshake, as deployed in the popular IEEE 802.11 MAC protocol [1] and some other protocols, requires a pair of sending and receiving nodes to exchange short request-to-send (RTS) and clear-to-send (CTS) packets before the actual transmissions of data and acknowledgment (ACK) packets. Other nodes that overhear RTS or CTS packets need to defer their access to the shared channel to avoid collisions. Though these collision avoidance schemes perform much better than

the simple carrier sense multiple access (CSMA) protocols in ad hoc networks, their performance still degrades rapidly when the number of nodes competing for a shared channel increases moderately. This is because those nodes within the range of a pair of sending and receiving nodes are refrained from both initiating and returning a handshake during the time, and nodes two hops away from either the sender or the receiver can be affected and this greatly reduces the possible spatial reuse.

Hence, limiting the size of the area that the handshake between sending and receiving nodes can influence is very desirable, and can be achieved with space division. Consequently, several schemes based on directional antennas have been proposed recently to enhance the performance of existing omni-directional collision-avoidance schemes [2]–[6]. In these schemes, which we call *directional collision avoidance* protocols, RTS and CTS packets are transmitted either omni-directionally or directionally depending on the design tradeoff between spatial reuse and collision avoidance, and data and ACK packets are transmitted directionally to reduce the interference to neighboring nodes.

The majority of the performance analysis of directional collision avoidance schemes has been done via simulations [2]–[6], and there is little prior work on the analytical modeling of directional collision-avoidance protocols. Wang and Garcia-Luna-Aceves [7] extended the model by Takagi and Kleinrock [8] to analyze three directional collision-avoidance schemes based on omni-directional packet reception, together with omni-directional and directional transmissions. The limitation of that work is that it assumes that the gain for omni-directional transmissions is the same as that for directional transmissions, and that all packet reception is omni-directional. In current systems, it is possible to have directional packet reception, and the range of directional transmissions can be longer than the range of omni-directional transmissions.

Section II reviews recent work on directional collision avoidance schemes, and Section III outlines the directional collision avoidance schemes that we study analytically and by simulation. The schemes we address consider that nodes communicate directly only with neighboring nodes within their omni-directional transmission range. The rationale for this approach is that, as our study shows, allowing nodes to obtain information about the relative location of neighboring

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nodes can be easily done with broadcast transmissions, without degrading the system performance considerably.

Section IV presents the first analytical study of directional collision avoidance in ad hoc networks that considers (a) the effect of directional transmitting and receiving on spatial reuse and collision avoidance, and (b) the effect of the differences in gains between omni-directional and directional transmissions. Our model generalizes the analytical model adopted in [7]. To attain a tractable analytical model, we assume that interference due to side lobes and outside the transmission beamwidth are negligible. Although this is not the case with real directional antennas, our model does provide a good approximation for ad hoc networks in which any node communicates with only those other nodes that reside within its omni-directional transmission range. The results of the analysis show that the scheme that uses both narrow-beam directional transmissions and receptions throughout the collision-avoidance handshake can achieve the best performance among all the schemes investigated, and that one-hop throughput does not degrade by increasing the number of competing nodes within a neighborhood because of the increased spatial reuse. It is also shown that, as expected, the performance of directional collision avoidance schemes degrades when directional transmissions have much higher gain than omni-directional transmissions, because of the increased interference range and reduced spatial reuse.

The analytical model we use assumes a priori knowledge of the position of neighbors around a node. Section V presents the results of simulations carried out to validate the results from the analytical model, as well as to analyze the effect of using broadcast beacons to communicate relative node location information among neighboring nodes. The IEEE 802.11 MAC protocol and its variants that implement directional collision avoidance are investigated.

The results obtained via simulations validate the results predicted by our analytical model. It is further shown that directional reception helps to cancel out almost all the adverse effects of hidden terminals, and achieves very low data packet collision ratio. The simulation results also show that the presence of broadcast traffic does not degrade the performance of the all-directional scheme more than the other schemes that combine directional and omni-directional transmissions, and that the degradation in throughput is small even for large percentages of broadcast traffic. This indicates that a practical and efficient implementation of directional collision avoidance consists of nodes broadcasting beacons of their presence and location periodically, listening omni-directionally while not transmitting or expecting to receive directional packet, and transmitting and listening directionally otherwise.

Section VI summarizes our results and outlines directions for future work.

II. RELATED WORK

There have been many proposals to modify the existing omni-directional IEEE 802.11 MAC protocol to take advantage of directional antennas in the recent past.

Ko et al. [2] proposed two schemes. One scheme consists of nodes using directional transmission of RTS packets and omni-directional transmission of CTS packets in collision avoidance, and then using directional transmissions of data and ACK packets after successful exchange of RTS and CTS packets. The other scheme consists of nodes using both directional and omni-directional transmissions of RTS packets alternately when nodes' locations are not always known. These two schemes show the tradeoff between increased possibility of simultaneous transmissions by neighboring nodes (scheme one) and reduced possibility of collisions of control packets (scheme two).

Nasipuri et al. [3] proposed a MAC protocol similar to those summarized above, but used a different model. The authors also assumed that directional reception capability is available. However, the authors do not consider the effects of possible difference in gain between omni-directional and directional transmissions and the simulations are limited to rather regular network topologies.

Ramanathan [4] studied the performance of beamforming antennas in ad hoc networks when RTS and CTS packets are transmitted omni-directionally with the same range as directional transmissions while data and ACK packets are transmitted directionally. The author also addressed some interesting problems arising from directional transmissions, such as link power control and directional neighbor discovery.

In the work done by Takai et al. [5] and Choudhury et al. [6], direction information is included in the network allocation vector (NAV), which is used by nodes in IEEE 802.11 to notify other nodes how long they should defer their access to the shared channel. With detailed direction information, a node receiving NAV from one direction can still transmit in other directions. Choudhury et al. [6] also proposed a multi-hop RTS scheme to take advantage of the higher gain in directional transmissions. The authors also show the importance of considering the different ranges of omni-directional and directional transmissions as the results may be quite different from those when omni-directional and directional transmissions are assumed to have similar ranges.

In addition to the recent surge of simulation-based study of directional collision avoidance schemes in ad hoc networks (e.g., [9], [10]), some researchers have also begun to use analytical models to evaluate the performance of directional collision avoidance protocols. Wang and Garcia-Luna-Aceves [7] used a simple model to analyze three MAC schemes that use omni-directional packet reception together with omni-directional transmissions, directional transmissions, or a combination of both. This model was first used by Takagi and Kleinrock [8] to derive the optimal transmission range of a node in a multi-hop network, and was used subsequently by Wu and Varshney [11] and Wang and Garcia-Luna-Aceves [12] to derive the throughput of non-persistent CSMA, some variants of busy tone multiple access (BTMA) protocols [13] and the traditional omni-directional RTS/CTS based collision avoidance scheme in multi-hop ad hoc networks, respectively. As we have stated, the limitation of the

analytical work presented in [7] is that the authors assume that omni-directional and directional transmissions have the same range, and consider only the case of omni-directional packet reception.

III. DIRECTIONAL COLLISION AVOIDANCE SCHEMES

In the omni-directional MAC scheme, all packet transmissions and receptions are omni-directional. The IEEE 802.11 MAC protocol is an example of a protocol based on this scheme. We call this scheme *OTOR* (for "omni-directional transmission and omni-directional reception").

We consider two directional collision-avoidance schemes in our analytical study. In both schemes, RTS, CTS, data packets and ACK are transmitted directionally. When a node is transmitting in one direction, it appears "deaf" to other directions and cannot sense any channel activity at all. In these schemes, spatial reuse is maximized as nodes limit their transmission to as small area as possible. They differ in whether directional receiving is used or not.

One scheme uses omni-directional receiving mode whenever it is not transmitting; we call such a scheme *DTOR*, which is short for "directional transmission and omni-directional reception." In the other scheme, which we call *DTDR* (for "directional transmission and directional reception"), a node directs its antenna to the neighbor from which it expects to receive a packet, such as a CTS, a data packet, or an ACK, and appears "deaf" to transmissions from other directions. A node that is not expecting a packet from a neighbor listens to the channel omni-directionally. If a node does not receive an expected packet within its due time, the node returns to omni-directional receiving mode.

It is also possible to establish schemes that combine both omni-directional and directional transmissions and receptions. For example, in one scheme, only CTS packets are transmitted omni-directionally, while all the other types of packets are transmitted directionally. The purpose of the omni-directional transmission of CTS packets would be to try to silence the neighbors of a receiver and to prepare a clear *floor* for the sending node. Omni-directional or directional reception can be applied to this approach. However, directional reception is intuitively more attractive, and results in the *MTDR* scheme (short for "mixed-directional transmission and directional reception").

To implement any of the directional collision avoidance schemes, nodes have to know the relative locations of their neighbors. In practice, exact locations of nodes' neighbors are not required for directional collision avoidance schemes to function. Generally speaking, the angle of arrival (AoA) information reported by the radio can be cached and used later to direct antenna orientation.

In this paper, we assume that broadcast beacons are used by nodes to determine who their neighbors are and their relative locations. Hence, even though a node can transmit and receive directionally, it communicates directly only with nodes within its omni-directional transmission range. The rationale for this approach derives from the results obtained in our analysis. Our analytical model studies the case in which location information is already known, and computer simulations are used to verify the results from this model and to show that even a crude and simple beaconing mechanism in which nodes let their neighbors know about their existence (and relative location) using periodic broadcast transmissions suffices to support directional collision avoidance schemes without a significant impact on performance.

IV. APPROXIMATE ANALYSIS

In this section, we present the analysis of the *DTOR* and *DTDR* schemes and compare their performance with the existing omni-directional *OTOR* scheme. The *MTDR* scheme can be analyzed using the approach presented here, but its analysis is omitted for brevity. However, it is still compared with the other schemes later in simulations.

A. Assumptions

For ease of explanation, we assume that directional transmissions and receptions have equal beamwidth, though it is trivial to extend the analysis to the case when their beamwidths are unequal.

Most of the assumptions made in our analysis of directional collision avoidance schemes have been used successfully in the performance evaluation of several MAC protocols [7], [8], [11], [12], [14] to obtain tractable analytical models.

As we have stated, to make the analysis of a multi-hop network tractable, we follow the line of modeling first used by Takagi and Kleinrock [8]. In this network model, the nodes are two dimensionally Poisson distributed with density λ, i.e., the probability $p(i, S)$ of finding i nodes in an area of S is given by:

$$p(i, S) = \frac{(\lambda S)^i}{i!} e^{-\lambda S}.$$

Varying λ has the effect of changing the congestion level within a region, as well as the number of hidden terminals.

The range of an omni-directional transmission is R, and the range of a directional transmission is $R' = \gamma R$, where $\gamma \geq 1$. Suppose N is the average number of nodes within a circular region of radius R; therefore, we have $N = \lambda \pi R^2$. Similarly we have $N' = \lambda \pi R'^2 = \gamma^2 N$.

We assume that nodes operate in time-slotted mode, with time slots of length equal to a propagation delay τ, which is much smaller than the length of any packet. Given that τ is very small, the performance of the time-slotted protocol is very close to the performance of the asynchronous version of the protocol, because the time-slotted version of the protocol delays the transmission of a packet by only a propagation delay that tends to 0. However, the analysis of the time-slotted version of the protocol is far simpler than the analysis of the pure protocol.

The transmission times of RTS, CTS, data, and ACK packets are normalized with regard to τ and are denoted by l_{rts}, l_{cts}, l_{data}, and l_{ack}, respectively. For the sake of simplicity, we also assume that all packet lengths are multiples of the length of a time-slot.

We derive the throughput of directional collision avoidance schemes based on a heavy-traffic assumption (i.e., a node always has a packet to be sent) which is reasonable given that nodes in ad hoc networks are busy sending both data and network-level signaling packets. We also assume that a silent node begins transmission with probability p at each time slot. Obviously, p cannot be 1 due to the way in which collision avoidance operates, such as deferring and backing off. Thus p is a protocol-specific parameter but is slot independent.

In the analysis done in [11], [12], it is assumed that a node becomes ready independently with probability p_0 at the beginning of each time slot. It is also assumed that a node initiates a successful handshake with any other node with probability p_s. Obviously, relationship between these quantities is that $p_s < p < p_0$. To be specific, $p = p_0 \cdot \text{Prob.}\{$Channel is sensed idle in a slot$\}$. In [11], [12], two Markov chains are used to analyze the performance of CSMA, BTMA, and RTS/CTS based collision avoidance with omnidirectional antennas. A Markov chain of the shared channel is used to derive the rough relationship between p and p_0, and a Markov chain is used to model the state of a node to derive the throughput. It is shown that the throughput is largely decided by p.

For any collision avoidance scheme to operate properly, p must be kept very small. Accordingly, as advocated in [7], rather than trying to derive a relationship between p and p_0, we simply assume that p takes on a range of values and then derive the throughput using the node model only. Given that the key objective of the model is to provide a comparative analysis of collision-avoidance strategies, and that the probability of successful handshakes by any one node in an ad hoc network cannot be very large, this approximation is very sensible, and is validated subsequently in our simulation analysis.

The node model is a three-state Markov chain shown in Fig. 1(from Fig. 1 in [7]), where *wait* is the state when the node defers for other nodes or backs off, *succeed* is the state when the node can complete a successful four-way handshake with other nodes, and *fail* is the state when the node initiates a handshake that is unsuccessful or cannot be completed due to collisions.

When a node transmits directionally, its transmissions can have longer range than its omni-directional transmissions. The effect of this is that a receiver can have more interfering sources than the nodes within an omni-directional transmission range. In our analysis and simulations, we assume that a node communicates directly only with other nodes that are within its omni-directional transmission range R, and communicate only indirectly with nodes outside R and inside its directional transmission range R', even though it can still be an interfering source for these nodes. The rationale for this assumption is twofold. First, in any directional collision avoidance scheme, a node needs to find the location of the nodes around it to direct its packet transmissions and receptions, and a simple way to accomplish this is by means of omni-directional beacons, especially in ad hoc networks in which nodes can be mobile. Second, it is possible to reduce the transmission power of
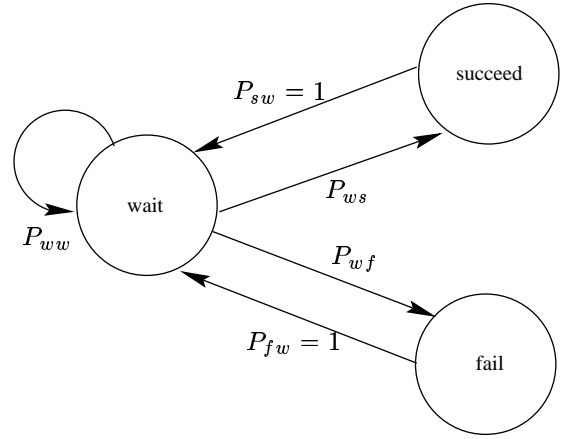

Fig. 1. Markov chain model for a node

directional transmissions to attain transmission ranges similar to those of omni-directional transmissions [10], in which case omni-directional and directional transmissions have the same range.

B. Throughput

The throughput Th of each directional collision avoidance scheme can be calculated by the proportion of time that a node spends transmitting data packets successfully in the average. With some simplifications, all the directional collision avoidance schemes we address in this paper can be analyzed using the same node model of Fig. 1, and differ only in the duration of certain states and the transition probabilities among these states. Let π_s, π_w and π_f denote the steady-state probability of state *succeed*, *wait* and *fail* respectively. From the node model of Fig. 1 we have:

$$Th = \frac{\pi_s \cdot l_{data}}{\pi_w T_w + \pi_s T_s + \pi_f T_f}. \tag{1}$$

where T_s, T_f and T_w are the duration of states *succeed*, *fail* and *wait*, respectively.

We first derive those steady-state probabilities, transition probabilities and times spent at different states that are common to *DTOR* and *DTDR*, and then derive the results that are particular to each scheme.

For the sake of simplicity, we regard *succeed* and *fail* as the states when two different kinds of *virtual* packets are transmitted.

In all the directional collision avoidance schemes, the duration in time slots of a node in the *succeed* state is

$$T_s = (l_{rts} + 1) + (l_{cts} + 1) + (l_{data} + 1) + (l_{ack} + 1)$$
$$= l_{rts} + l_{cts} + l_{data} + l_{ack} + 4.$$

Because by assumption collision avoidance is enforced at each node in all the schemes we consider, no node is allowed to transmit data packets continuously; therefore, as shown in Fig. 1, the transition probabilities from *succeed* to *wait* and from *fail* to *wait* are both one, and the transition probabilities from *succeed* to *succeed* and from *fail* to *fail* are both zero.

Given that a node in the *wait* state listens omni-directionally, the transition probability P_{ww} that node x continues to stay in

wait state in a slot equals the probability that it does not initiate any transmission and there is no node around it initiating a transmission in the direction towards node x. Because this two events are independent, we have that

$$P_{ww} = (1-p)e^{-p'N'}. \tag{2}$$

From Fig. 1, we have that the steady-state probability of the *wait* state equals

$$\pi_w = \pi_w P_{ww} + \pi_s P_{sw} + \pi_f P_{fw} \tag{3}$$

Noting that $\pi_s + \pi_f = 1 - \pi_w$, and substituting the results presented above for P_{sw}, P_{fw} and P_{ww} in Eq. (3), we obtain

$$\pi_w = \pi_w P_{ww} + \pi_s P_{sw} + \pi_f P_{fw} = \pi_w P_{ww} + \pi_s + \pi_f$$
$$\pi_w = \pi_w P_{ww} + 1 - \pi_w$$
$$\pi_w = \frac{1}{2 - P_{ww}} \tag{4}$$
$$= \frac{1}{2 - (1-p)e^{-p'N}}.$$

The steady-state probability of *succeed* state π_s can be calculated by $\pi_s = \pi_w P_{ws} + \pi_s P_{ss}$. Given that $P_{ss} = 0$, we can use Eq. (4) to express π_s as a function of P_{ws} as follows:

$$\pi_s = \pi_w P_{ws} = \frac{P_{ws}}{2 - (1-p)e^{-p'N}}.$$

To derive the transition probability P_{ws} from *wait* to *succeed*, we need to calculate the probability $P_{ws}(r)$ that node x successfully initiates a four-way handshake with node y at a given time slot when the two nodes are at a distance r apart. The configuration is shown in Fig. 2, where θ is the beamwidth of transmissions and receptions. In Fig. 2, solid circles indicate omni-directional transmission ranges of nodes, while dashed circles indicate directional transmission ranges.

It is important to note that this analytical model assumes complete attenuation of the transmitted signal outside the range of the transmission beamwidth, and does not consider the effect of side lobes present in directional transmission and reception which is the subject of future work. The rationale for this simplification, which makes the model much more tractable, derives from the fact that nodes are required to communicate directly only with nodes within their omni-directional transmission range. Accordingly, the likelihood that a receiver y in the *wait* state engages in a handshake that is disrupted by either the main transmission beamwidth or a side lobe from neighboring node z within a directional reception side lobe of y is very small. If the transmission beamwidth of x is wide, node z is likely to listen to the transmission from node x when y does; if the beamwidths of nodes x and y are narrow, node z is unlikely to affect node y, unless it is almost collocated with y and this event has a very small probability according to the Poisson deployment of nodes on the plane.

The success of the handshake between nodes x and y depends on the nodes for which y is within their omni-directional transmission range and those nodes for which y
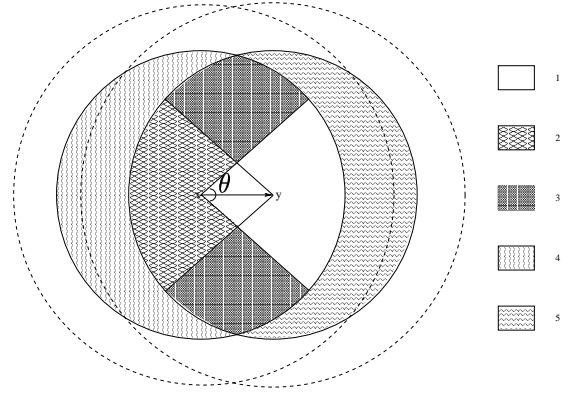

Fig. 2. *DTOR* scheme

is within their directional transmission range. Fig. 2 indicates in dashed lines the area around nodes x and y that may contain nodes whose directional transmissions can reach x or y. To simplify our computation of throughput, we assume that there are, in effect, N' nodes around a node's omni-directional transmission range, though no node is assumed to communicate directly with any other node that is only reachable from directional transmissions. In fact, this simplifying assumption avoids the complexity of calculating interference directly from those nodes that are between the solid and dashed circles and instead such interference is taken into account by increasing the number of nodes within omni-directional range from N to N'.

From Fig. 2, we can see that the region around nodes x and y can be divided into five areas. Denote by S_i the size of Area i, the size of each of the five areas are:

$$S_1 = \theta/(2\pi)$$
$$S_2 = \theta/(2\pi) - r^2 \tan(\theta/2)/(2\pi)$$
$$S_3 = 2q(r/2)/\pi - \theta/\pi + r^2 \tan(\theta/2)/(2\pi)$$
$$S_4 = 1 - 2q(r/2)/\pi$$
$$S_5 = 1 - 2q(r/2)/\pi \tag{5}$$

where we have normalized r with regard to R by setting $R = 1$ and S_i with regard to πR^2, and $q(t) = \arccos(t) - t\sqrt{1-t^2}$. The calculation of these areas is straightforward and omitted here.

With the above definitions, $P_{ws}(r)$ equals the probability that x does not transmit in a given time slot, y does not transmit in the same time slot, and none of the nodes in the five areas defined above interfere with the handshake between x and y. Given that transmissions are independent, we have:

$$P_{ws}(r) = p_x \cdot p_y \cdot \prod_{i=1}^{5} p_i$$

where

$$p_x = \text{Prob.}\{x \text{ transmits in the time slot}\} = p,$$
$$p_y = \text{Prob.}\{y \text{ does not transmit in the time slot}\} = 1 - p,$$
$$p_i = \text{Prob.}\{\text{none of the nodes within Area } i \text{ interfere} $$
$$\text{with the handshake between } x \text{ and } y \}.$$

5

Computing the various probabilities p_i requires us to compute the probability P that no node transmits in a time slot within a planar area of size S in which nodes are randomly placed according to a two-dimensional Poisson distribution. This probability equals

$$
\begin{aligned}
P &= \sum_{i=0}^{\infty} (1-p)^i \frac{(\lambda S)^i}{i!} e^{-\lambda S} \\
&= \sum_{i=0}^{\infty} \frac{[(1-p)\lambda S]^i}{i!} e^{-(1-p)\lambda S} \cdot e^{-p\lambda S} \\
&= e^{-p\lambda S} = e^{-pS\lambda\pi R^2/(\pi R^2)} \\
&= e^{-pNS/(\pi R^2)}.
\end{aligned}
\tag{6}
$$

The next two subsections compute the remaining periods and probabilities needed to compute the throughput of the *DTOR* and *DTDR* schemes.

C. DTOR

Because the *DTOR* scheme cannot prevent interference from neighboring nodes, the handshake between any pair of sending and receiving nodes may be interrupted at any time. Consequently, the failed period T_f can last from $T_1 = l_{rts} + 1$ to $T_2 = l_{rts} + l_{cts} + l_{data} + l_{ack} + 4$.

Given that transmissions start at slot boundaries, we assume that the length of the failed period follows a truncated geometric distribution with parameter p, with a lower bound T_1 and an upper bound T_2. We can then consider T_f to be the mean value of the truncated geometric distribution, which is [7]:

$$
T_f = \frac{1-p}{1-p^{T_2-T_1+1}} \sum_{i=0}^{T_2-T_1} p^i (T_1 + i).
\tag{7}
$$

Obviously, the duration of a node in *wait* state T_w is 1.

In the following, we use the definitions of Areas 1 to 5 to compute the probability that there is no interference from nodes in each of those areas using Eq. (6).

The probability that no node in Area 1 interferes with the handshake between nodes x and y equals the probability that no node in the area transmits in the same time slot as node x does, which equals

$$
p_1 = e^{-pS_1 N'}.
$$

For no interference to exist from nodes in Area 2, it must be true that no node transmits in $2l_{rts}$ slots in the direction of node y and does not transmit in the slot when the transmission of node y arrives at them. Therefore,

$$
p_2 = e^{-p' S_2 N'(2l_{rts})} \cdot e^{-pS_2 N'}
$$

where $p' = p\theta/(2\pi)$.

In Area 3, no interference exists if no node transmits in the direction to nodes x and y during the whole handshake between the two nodes, and the span angle of the direction θ' is $\theta + \phi$, where ϕ is the angle formed by the two lines joining a node in Area 3 with nodes x and y if ϕ is less than θ; otherwise, θ' is just 2θ. When nodes x and y are very close

to each other, $\theta' \approx \theta$. Though the range of θ' is between θ and 2θ, for simplicity, we use $\theta' = \theta$. Therefore,

$$
\begin{aligned}
p_3 &= e^{-p'' S_3 N'(l_{rts}+l_{rts}+1+l_{cts}+1+l_{data}+1+l_{ack}+1)} \\
&= e^{-p'' S_3 N'(2l_{rts}+l_{cts}+l_{data}+l_{ack}+4)}
\end{aligned}
$$

where $p'' = p\theta'/(2\pi) = p\theta/(2\pi)$.

No interference to x and y exists from nodes in Area 4 if no node in that area transmits in node x's direction when node y is transmitting. Therefore, there are two such periods. One is the time when node y transmits a CTS packet to node x and the other is the time when node y transmits an ACK packet to node x. The durations of these two periods in the number of time slots are approximately $l_{rts} + l_{cts} + 1$ and $l_{rts} + l_{ack} + 1$ respectively which follows the assumption that nodes transmit in each time slot independently with probability p. Accordingly, the probability p_4 that no interference takes place from nodes in Area 4 is

$$
\begin{aligned}
p_4 &= e^{-p' S_4 N'(l_{rts}+l_{cts}+1)} \cdot e^{-p' S_4 N'(l_{rts}+l_{ack}+1)} \\
&= e^{-p' S_4 N'(l_{rts}+l_{cts}+1+l_{rts}+l_{ack}+1)} \\
&= e^{-p' S_4 N'(2l_{rts}+l_{cts}+l_{ack}+2)}.
\end{aligned}
$$

No interference exists from nodes in Area 5 if no node transmits in node y's direction when node x is transmitting. Similar to the previous case, there are two such periods. One is the time when node x transmits an RTS packet to node y and the other is the time when node x transmits a data packet to node y. The durations of these two periods in the number of time slots are approximately $l_{rts} + l_{rts} + 1$ and $l_{rts} + l_{data} + 1$ respectively. Therefore, the probability p_5 that no interference from nodes in Area 5 takes place is

$$
\begin{aligned}
p_5 &= e^{-p' S_5 N'(l_{rts}+l_{rts}+1)} \cdot e^{-p' S_5 N'(l_{rts}+l_{data}+1)} \\
&= e^{-p' S_5 N'(l_{rts}+l_{rts}+1+l_{rts}+l_{data}+1)} \\
&= e^{-p' S_5 N'(3l_{rts}+l_{data}+2)}.
\end{aligned}
$$

Because each sending node chooses any one of its neighbors with equal probability and the average number of nodes within a region of radius r is proportional to r^2, the probability density function of the distance r between nodes x and y is

$$
f(r) = 2r, \quad 0 < r < 1
$$

where we have normalized r with respect to R by setting $R = 1$.

Therefore, P_{ws} equals

$$
\begin{aligned}
P_{ws} &= \int_0^1 2r P_{ws}(r) dr \\
&= \int_0^1 2r \left(p \cdot (1-p) \cdot p_1 \cdot p_2 \cdot p_3 \cdot p_4 \cdot p_5 \right) dr.
\end{aligned}
$$

D. DTDR

Referring to Fig. 2, it is clear that, for the *DTDR* scheme, only nodes in Areas 1 and 2 can interfere with the handshake between nodes x and y. However, in the *DTDR* scheme, nodes are more vulnerable to the transmissions from nodes in these areas than they are in the *DTOR* scheme, because they receive omni-directionally only if they are in the *wait* state. To take

the higher vulnerability into account, we use $l_{rts} + l_{cts} + 2$ as the lower bound for the distribution of T_f.

On the other hand, because nodes x and y are immune to the transmissions from nodes in Areas 3, 4, and 5, and because concurrent transmissions can go on unobstructed in these areas, we introduce a spatial reuse factor $\gamma(r)$ for this scheme in the calculation of $P_{ws}(r)$. The parameter $\gamma(r)$ is defined to be the number of possible concurrent transmissions in the combined region covered by nodes x and y, i.e.,

$$\gamma(r) = \min(\gamma_1(r), \gamma_2(r))$$

In the above expression, $\gamma_1(r)$ is the ratio between the total region covered nominally by nodes x and y and the actual region covered by the handshake between nodes x and y. If there is one handshake in Areas 1 and 2, then in theory there can be possibly $\gamma_1(r)$ concurrent handshakes in the total area of Areas 1 to 5. Hence,

$$\gamma_1(r) = (S_1 + S_2 + S_3 + S_4 + S_5)/(S_1 + S_2).$$

On the other hand, $\gamma_2(r)$ can be explained as follows: There are on average $N \cdot (S_3 + S_4 + S_5)$ nodes in the area of Areas 3 to 5 and in theory they can form a maximum of $\gamma_2(r) = N \cdot (S_3 + S_4 + S_5)/2$ pairs of concurrent handshakes. To be conservative, we take the smaller value of $\gamma_1(r)$ and $\gamma_2(r)$ to estimate the spatial reuse benefit enabled by the *DTDR* scheme.

The above is a very crude estimation of the gain in spatial reuse for the *DTDR* scheme, because the area unaffected by the handshake between nodes x and y cannot be used fully by their neighbors. Still, for this scheme, P_{ws} can be adjusted as follows:

$$P_{ws} = \int_0^1 2r\gamma(r)P_{ws}(r)dr.$$

The other quantities needed to derive the throughput are the same as those for the *DTOR* scheme.

E. Analytical Results

We compare the performance of the *OTOR*, *DTOR* and *DTDR* schemes. For the *OTOR* scheme, we use the results reported by Wang and Garcia-Luna-Aceves [7], who assume that correct collision avoidance is enforced, i.e., once a node starts sending a CTS packet in reply to an RTS destined to it, the following handshake can go on unobstructed. The performance of *OTOR* with this assumption constitutes an upper bound of the performance that can be attained with IEEE 802.11 MAC protocol, in which data packets may collide with other packets due to the additional imperfect collision avoidance.

We present the results of two typical configurations for the three schemes; similar results can be readily obtained for other configurations. In these configurations, τ denotes the duration of one slot and RTS, CTS, and ACK packets last 5τ, while a data packet lasts 100τ. In configuration one, both omni-directional and directional transmissions have the same gain and thus we have $N' = N$. In configuration

two, directional transmissions have higher gain than omni-directional transmissions and $\gamma = 1.5$. In this case, $N' = 1.5^2 N = 2.25N$.

For each configuration, we derive the maximum achievable throughput when the antenna beamwidth changes from $\theta = 15°(\frac{\pi}{12})$ to $\theta = 120°(2\pi/3)$ in increment of $\theta = 15°(\frac{\pi}{12})$. The results for configurations one and two are shown in Figs. 3 and 4, respectively.

Figs. 3 and 4 clearly show that the *DTDR* scheme maintains the highest throughput among the three schemes, even with the increase of transmission and receiving beamwidth. Two factors contribute to the superiority of the *DTDR* scheme. One is the significant increase in spatial reuse, because only a small area is covered by the transmissions between two nodes engaged in a handshake according to the analysis. The other is the much reduced interference from those nodes that are not aware of the handshake because of directional receiving.

Even though the *DTDR* scheme does not ensure perfect collision avoidance, the directional reception capability makes the receiving node immune to the transmissions from many other nodes in Areas 3, 4, and 5 after it transmits a CTS packet. Hence, in terms of avoiding collisions, the *DTDR* scheme is as good as or even better than the *OTOR* scheme, which silences all the neighbors around both a sender and a receiver.

Another significant advantage of the *DTDR* scheme is that its performance does not degrade with the increase of competing nodes within a neighborhood when antenna beamwidth is narrow. Instead, it even has a slight increase in throughput. This can be explained as follows: When the number of nodes is small, spatial reuse may be not utilized to its full advantage because some nodes may have to stay idle when all of their neighbors are engaged. This is not due to collision avoidance, but due to the scarity of nodes. Hence, when more nodes are around, the effect of spatial reuse is more conspicuous and one-hop throughput increases accordingly.

The results in Figs. 3 and 4 also show that, as expected, the performance of the *DTOR* and *DTDR* schemes degrades when directional transmissions have higher gain than omni-directional transmissions. This is a direct consequence of the fact that the higher gain of directional transmissions leads to more interference at nodes receiving in omni-directional mode. However, it is clear that the *DTDR* scheme is superior to the *OTOR* scheme in all cases, and the same conclusion can be derived from the results of simulation experiments described in the next section. This helps to justify our approach of having each node consider as its neighbors those nodes that it hears through their omni-directional beacon transmissions.

V. SIMULATION RESULTS

This section describes the results of computer simulations used to investigate the performance of the popular IEEE 802.11 DFWMAC protocol, which is labeled as *OTOR* in this section, and its variants corresponding to three directional collision avoidance schemes. The directional schemes considered are the *DTOR*, *MTDR* and *DTDR* schemes.

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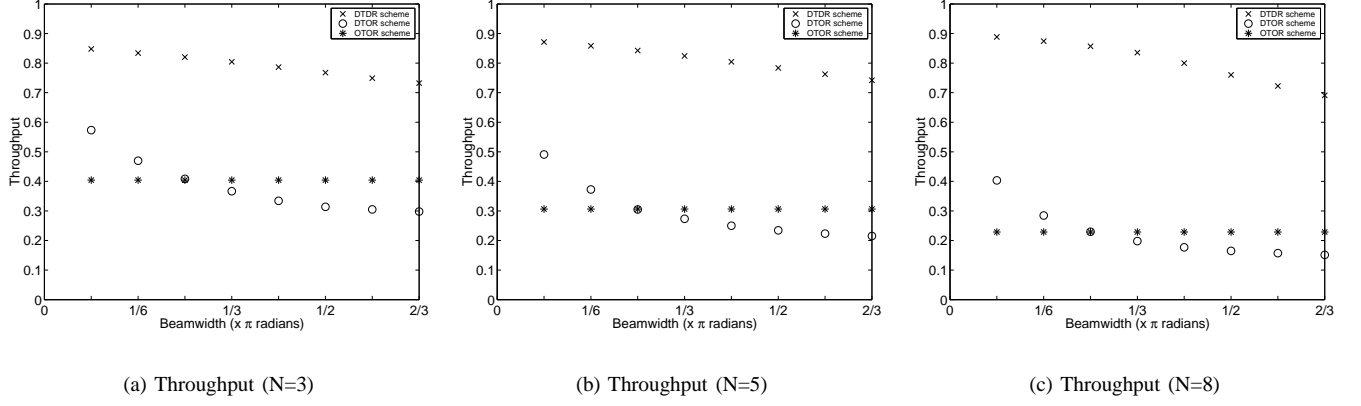(a) Throughput (N=3) (b) Throughput (N=5) (c) Throughput (N=8)

Fig. 3. Throughput comparison when omni-directional and directional transmissions have equal gain ($l_{rts} = l_{cts} = l_{ack} = 5\tau, l_{data} = 100\tau, \gamma = 1$).

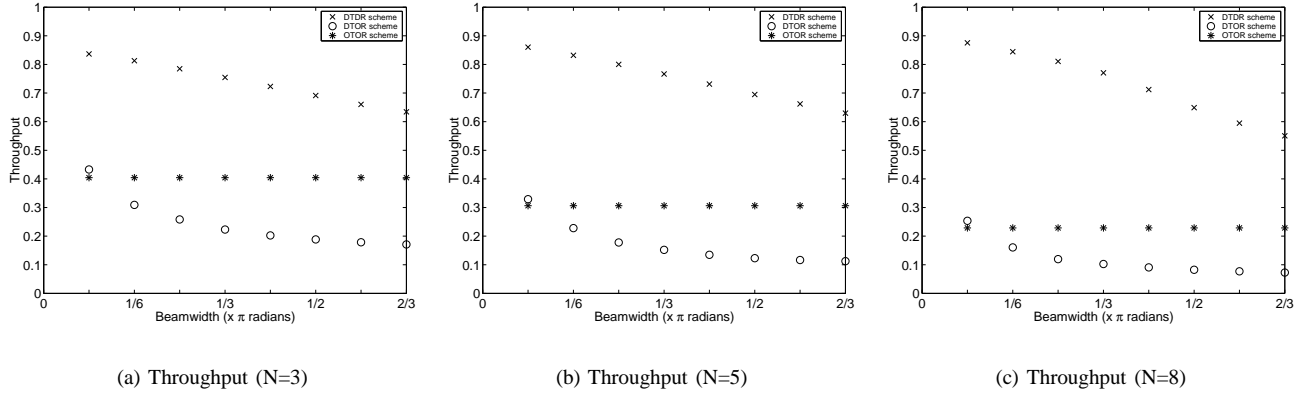(a) Throughput (N=3) (b) Throughput (N=5) (c) Throughput (N=8)

Fig. 4. Throughput comparison when the gain of directional transmissions equals one and a half times the gain of omni-directional transmissions ($l_{rts} = l_{cts} = l_{ack} = 5\tau, l_{data} = 100\tau, \gamma = 1.5$).

We use GloMoSim 2.0 [15] as the network simulator and implement the directional collision avoidance schemes under the assumption that there is a neighbor protocol that maintains a list of neighbors as well as their locations by means of beacons transmitted omni-directionally and periodically.

Given that we assume that location information is refreshed periodically by means of broadcast transmissions, it is important to investigate the impact of broadcast traffic on directional collision avoidance schemes. Accordingly, our simulations include two parts. We first present the performance of directional collision avoidance schemes when only unicast traffic is present in the network, which corresponds to the case in which location information is always known a priori. We then present the performance of the same schemes with different degrees of broadcast traffic, which results from beaconing location information with different degrees of persistence.

A. Performance Evaluation for Unicast Traffic

Direct sequence spread spectrum (DSSS) parameters are used throughout the simulations, which are shown in Table I. The raw channel bit rate is 2Mbps. We use a uniform distribution to approximate the Poisson distribution used in our network model, which is mainly used to facilitate our derivation of analytical results. Even though the network model follows a uniform distribution, nodes in this model are distributely much less regularly than the grid model used in prior work, because nodes can have different number of one-hop neighbors and two-hop neighbors in different directions. In this network model, we place nodes in concentric circles or rings. That is, given that a node's transmitting and receiving range is R and that there are on average N nodes within this circular region, we place N nodes in a circle of radius R, subject to a uniform distribution. Because there are on average 2^2N nodes within a circle of radius $2R$, we place $2^2N - N = 3N$ nodes outside the previous circle of radius R but inside the concentric circle of radius $2R$, i.e., the ring with radii R and $2R$, subject to the same uniform distribution. Then $3^2N - 2^2N = 5N$ nodes can be placed in an outer ring with radii $2R$ and $3R$.

Because we cannot generate an infinite network model, we just focus our attention on the performance of the innermost N nodes. According to our experiments, conclusions drawn from a circular network of radius of more than $3R$ will not affect the conclusion to be drawn in this section, i.e., boundary effects
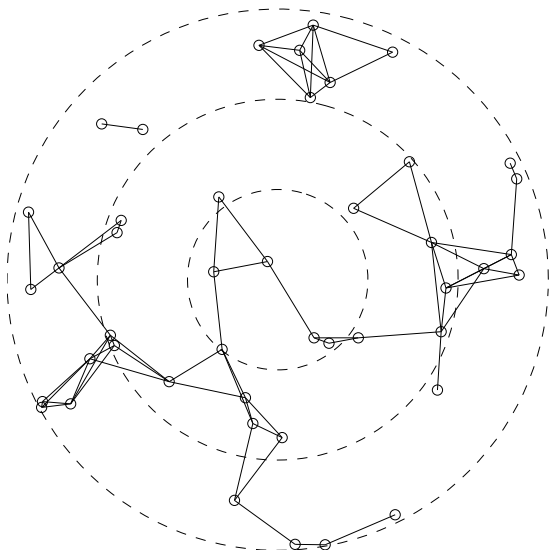
8

frag replacements

Fig. 5.   A sample network topology when $N = 5$

RTS	CTS	data	ACK	DIFS	SIFS
20-byte	14-byte	1460-byte	14-byte	50μsec	10μsec
contention window		slot time	sync. time	prop. delay	
	31–1023	20μsec	192μsec	1μsec	

can be safely ignored when the circular network's radius is $3R$. Therefore, we present only the results for a circular network of radius $3R$. To avoid some extreme cases, we only use network topologies that satisfy the following requirements:

- For the inner N nodes, each node should have at least 2 neighbors and at most $2N - 2$ neighbors.
- For the intermediate outer $3N$ nodes, each node should have at least 1 neighbor and at most $2N - 1$ neighbors.

Fig. 5 illustrates a sample network topology used in our simulations when $N = 5$.

In our simulation, each node has a constant-bit-rate (CBR) traffic generator with data packet size of 1460 bytes, and one of its neighbors is randomly chosen as the destination for each packet generated. All nodes are always backloged. We run simulation programs with $N = 3$, 5, and 8, and for each choice of N we use beamwidth values of $\theta = 30°$, $90°$, and $150°$. The same beamwidth is used for directional transmissions and receptions. It may be noted that both beamwidth and gain may not be adjusted independently in some current antenna systems. However, computer simulations do not need to be constrained by the capability of existing systems and it is expected that simulation results can provide insight or motivation for the design of more suitable antenna systems which we will show later.

Fifty random topologies were generated that satisfy the uniform distribution and the averages of the throughput and delay for the N nodes in the innermost circle of radius R were computed for each configuration.

The results for the case in which omni-directional and directional transmissions have equal gain are shown in Figs. 6 and 7. The results for the case in which directional transmissions have higher gain than omni-directional transmissions and $\gamma = 1.5$ are shown in Figs. 8 and 9.

In Figs. 6–9, the vertical lines show the range of throughput/delay achieved by each scheme, i.e., *mean ± standard variance*. The lines are shifted a bit for clarity. The *DTDR* scheme performs the best among all these schemes and its performance does not degrade even for large values of N as predicted in the analysis. The results also show that the *MTDR* scheme outperforms the *DTOR* scheme, which indicates that the directional receiving capability can boost performance significantly.

Without directional receiving, a scheme with mixed transmissions (*MT* scheme) performs worse than a scheme with only directional transmissions (*DT* scheme). This is because omni-directionally transmitted CTS packets make almost all the nodes around the receiver defer their access to the shared channel or interfere with the ongoing handshake around the nodes that transmit CTS packets. Such conservative collision avoidance can largely nullify the benefits of spatial reuse and an all-directional scheme such as *DT* is shown to perform much better than *MT* when both schemes use only directional transmission capability of antenna systems.
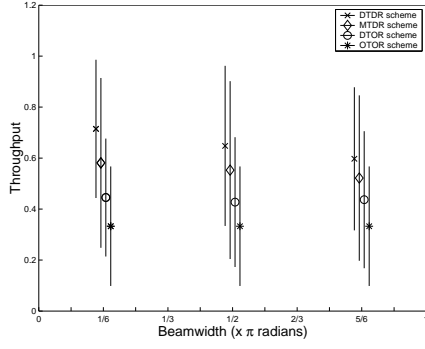
However, when directional receiving is used, even though CTS is transmitted omni-directionally, the handshakes of those nodes that have turned their receiving to other directions are not affected. Hence, the *MTDR* scheme can outperform the *DTOR* scheme in this case, although its performance is still inferior to the *DTDR* scheme because of the reduced spatial reuse.

It is also clear that, when beamwidth becomes wider, the performance of the *DTDR* scheme degrades faster when N becomes larger. This shows that when networks are dense, the performance of a directional scheme is more influenced by the transmission/reception beamwidth.
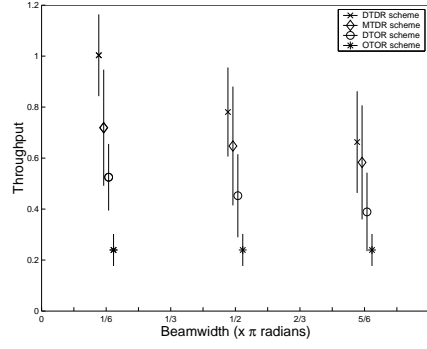
It should be noted again that, because correct collision avoidance is not enforced in the IEEE 802.11 MAC protocol, collisions of data packets can still occur and hence the *OTOR* scheme cannot achieve the same performance predicted in the analysis, which assumes correct collision avoidance. It is for this reason that the *DTOR* scheme performs better than the *OTOR* scheme, even when wider beamwidths are used.

When comparing the results shown in Figs. 6 and 7 with those in Figs. 8 and 9, it is clear that higher directional transmission gains can have negative effects on both throughput and delay. This is because a node's directional transmissions interfere with more nodes, which translates into a reduction in spatial reuse, given that more nodes spend more time in the wait state after perceiving the channel busy.
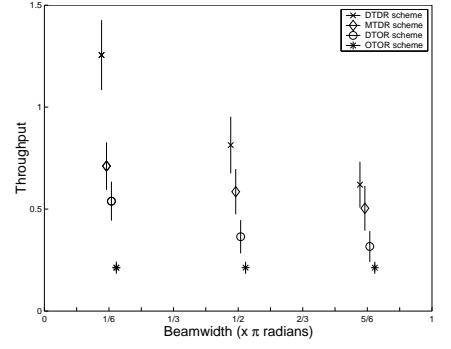
We also collected statistics about the number of transmitted RTS packets that lead to ACK timeouts due to collisions of data packets, as well as the total number of transmitted RTS packets that can lead to either an incomplete RTS-CTS-data handshake or a successful four-way handshake. Then we
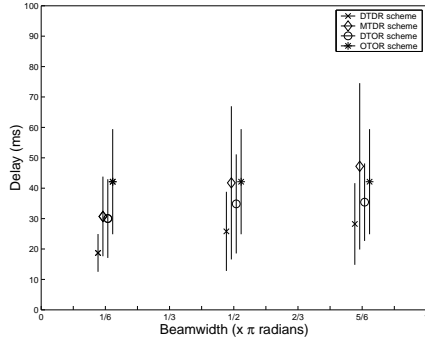
PSfrag replacements
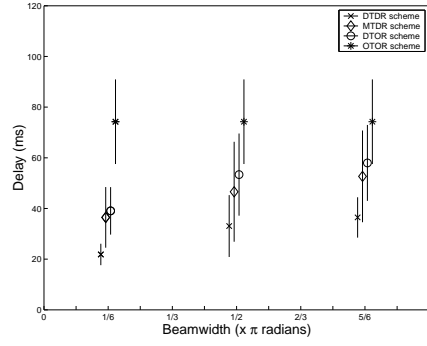
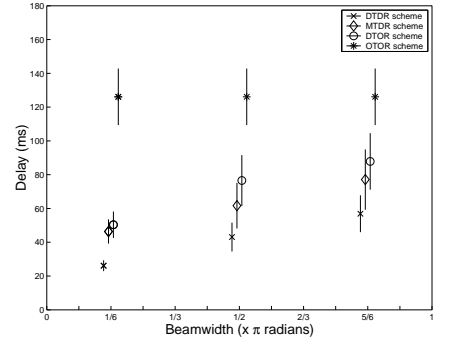Throughput

1.2

1

0.8

0.6

0.4

0.2

0

0   1/6   1/3   1/2   2/3   5/6   1
Beamwidth (x π radians)

DTDR scheme
MTDR scheme
DTOR scheme
OTOR scheme

(a) N=3

PSfrag replacements

Throughput

1.2

1

0.8

0.6

0.4

0.2

0

0   1/6   1/3   1/2   2/3   5/6   1
Beamwidth (x π radians)

DTDR scheme
MTDR scheme
DTOR scheme
OTOR scheme

(b) N=5

Throughput

1.5

1

0.5

0

0   1/6   1/3   1/2   2/3   5/6   1
Beamwidth (x π radians)

DTDR scheme
MTDR scheme
DTOR scheme
OTOR scheme

(c) N=8

Fig. 6.   Throughput Comparison – Equal Gain

PSfrag replacements

Delay (ms)

100
90
80
70
60
50
40
30
20
10
0

0   1/6   1/3   1/2   2/3   5/6   1
Beamwidth (x π radians)

DTDR scheme
MTDR scheme
DTOR scheme
OTOR scheme

(a) N=3

PSfrag replacements

Delay (ms)

120

100

80

60

40

20

0

0   1/6   1/3   1/2   2/3   5/6   1
Beamwidth (x π radians)

DTDR scheme
MTDR scheme
DTOR scheme
OTOR scheme

(b) N=5

Delay (ms)

180
160
140
120
100
80
60
40
20
0

0   1/6   1/3   1/2   2/3   5/6   1
Beamwidth (x π radians)

DTDR scheme
MTDR scheme
DTOR scheme
OTOR scheme

(c) N=8

Fig. 7.   Delay Comparison – Equal Gain

PSfrag replacements

Throughput

1.2

1

0.8

0.6

0.4

0.2

0

0   1/6   1/3   1/2   2/3   5/6   1
Beamwidth (x π radians)

DTDR scheme
MTDR scheme
DTOR scheme
OTOR scheme

(a) N=3

PSfrag replacements

Throughput

1.2

1

0.8

0.6

0.4

0.2

0

0   1/6   1/3   1/2   2/3   5/6   1
Beamwidth (x π radians)

DTDR scheme
MTDR scheme
DTOR scheme
OTOR scheme

(b) N=5

Throughput

1.2

1

0.8

0.6

0.4

0.2

0

0   1/6   1/3   1/2   2/3   5/6   1
Beamwidth (x π radians)

DTDR scheme
MTDR scheme
DTOR scheme
OTOR scheme

(c) N=8

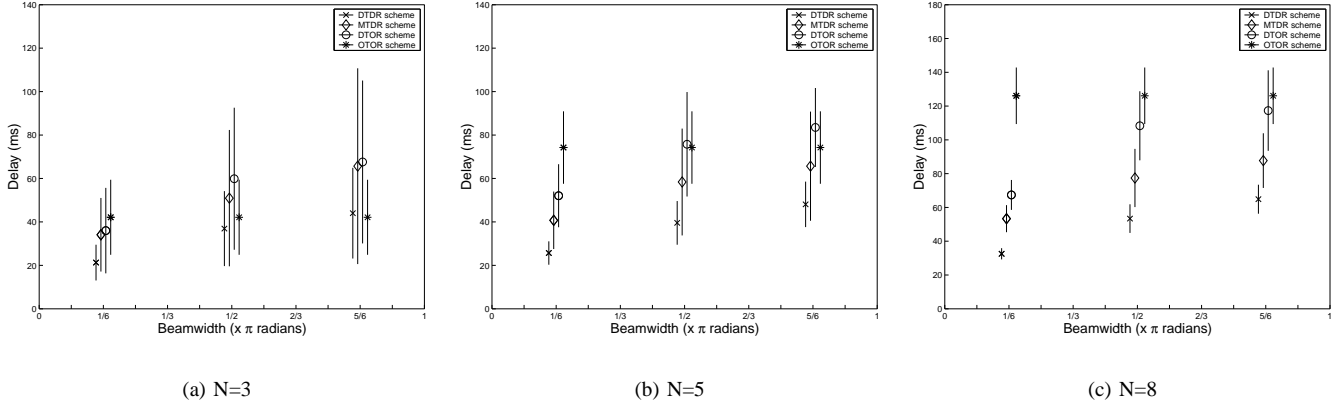Fig. 8.   Throughput Comparison – Higher Gain ($\gamma = 1.5$)

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Fig. 9. Delay Comparison – Higher Gain ($\gamma = 1.5$)

calculate the ratio of these two numbers which in fact shows the effectiveness of collision avoidance. The larger the ratio is, the worse the performance of the collision avoidance scheme becomes. The results are shown in Tables II and III.

The results in Tables II and III. show that directional collision avoidance schemes that do not employ directional receiving, such as the *DTOR* scheme, do have higher collision occurrences than the *OTOR* scheme. The reason for this result is that such directional schemes are more aggressive in achieving spatial reuse, but are unable to force all the neighbors around the sending and receiving nodes to defer access to the shared channel. However, the adverse effects of hidden terminals are still conspicuous even for the *OTOR* scheme according to the high collision ratio shown in the table. It is also clear that, in addition to high spatial reuse, the schemes with narrow receiving beamwidth have far smaller collision ratios than the schemes without directional receiving. Hence, with directional receiving, the adverse effects of hidden terminals are almost completely canceled, leading to much higher throughput. It can also be noted that higher directional transmission gain leads to higher data collision ratio due to the increased interference it introduces. Therefore, directional antenna systems that are able to transmit and receive with narrow beamwidth while having the capability to reduce the power of directional transmissions are much more desirable than other variants.

B. Impact of Broadcast Traffic

In this set of simulation experiments we use the same network topologies discussed for the unicast experiments. Each node is a constant bit rate (CBR) generator that continuously generates unicast data packets and broadcast data packets alternately. For unicast packets, the destination node is chosen randomly from the node's neighbors. The size of a unicast data packet is 1460-byte and the size of a broadcast data packet is 500-byte, about one third the size of a unicast data packet, which is sensible given that the main use for broadcast packets is the beaconing of the nodes' presence and location.

We use r to denote the ratio between the number of broadcast data packets generated and the total number of data packets generated. We vary the number (N) of nodes in the innermost circular region of radius R as well as r to obtain the unicast throughput which is the aggregate throughput contributed by the innermost N nodes sending unicast data packets that are acknowledged. We show the results in Figs. 10–12. In the directional schemes (*DT* and *MT*), directional receiving is not used, because the results with directional receiving are similar and are not presented here for brevity.

Figs. 10–12 show that the throughput of the three schemes degrades very slowly even in the case in which 30% of each node's traffic is broadcast.

The only exception to the general behavior pattern observed for all schemes is that the throughput of the *MTDR* scheme increases slightly for $N = 5$ and 8 when r increases from 0 to 0.1. It seems that in these cases a small percentage of broadcast traffic helps to interrupt some nodes' long waiting time for collision avoidance and thus nodes are more aggressive in access to the shared channel. For all other cases, broadcast traffic can degrade unicast throughput gradually, but not dramatically. In addition, for small values of N (such as 3), the three directional schemes perform almost the same, considering both mean and standard variance.

When N increases, the *DTOR* scheme with small beamwidth θ performs indisputably much better than the other two schemes. This can be explained as follows. When the network becomes more congested, it is very difficult for a pair of sending and receiving nodes to get coordinated with their one-hop and two-hop neighbors in the *OTOR* scheme. If coordination is not achieved, then their handshake may be disrupted with high probability by the omni-directional transmissions of neighboring nodes. Even if coordination is achieved, all their one-hop and two-hop neighbors are prohibited from transmitting and spatial reuse is greatly reduced. The same reason applies to *MTOR* scheme due to the omni-directional transmission of CTS packets. In the *DTOR* scheme, transmissions are confined to much smaller regions and mul-

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TABLE II

COMPARISON OF PERCENTAGE OF ACK TIMEOUTS IN DIFFERENT SCHEMES ($\gamma = 1$)

	DTDR			MTDR		
	30°	90°	150°	30°	90°	150°
N = 3	0.04±0.02	0.06±0.05	0.06±0.04	0.03±0.02	0.04±0.04	0.06±0.06
N = 5	0.05±0.01	0.08±0.03	0.11±0.05	0.04±0.01	0.08±0.04	0.13±0.07
N = 8	0.07±0.01	0.14±0.02	0.19±0.04	0.07±0.02	0.15±0.03	0.22±0.05

	DTOR			OTOR
	30°	90°	150°	N/A
N = 3	0.38±0.17	0.35±0.19	0.33±0.18	0.29±0.21
N = 5	0.46±0.07	0.45±0.11	0.44±0.12	0.39±0.10
N = 8	0.55±0.03	0.58±0.04	0.57±0.05	0.46±0.05

TABLE III

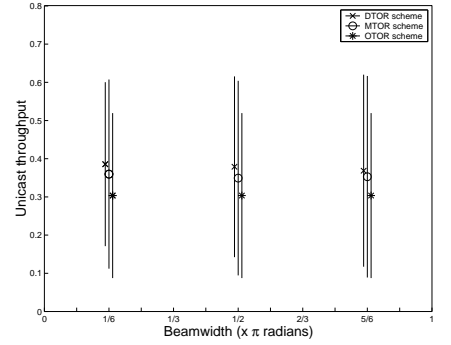COMPARISON OF PERCENTAGE OF ACK TIMEOUTS IN DIFFERENT SCHEMES ($\gamma = 1.5$)

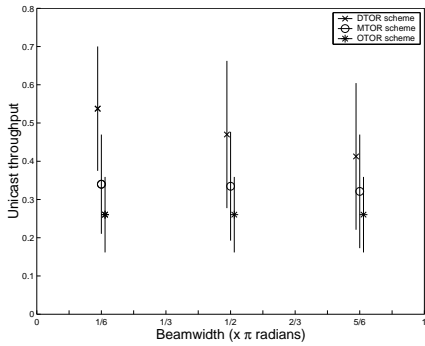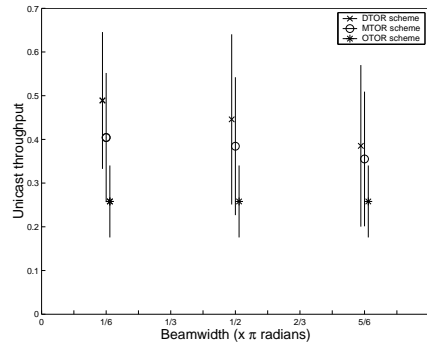|	DTDR			MTDR			DTOR		
	30°	90°	150°	30°	90°	150°	30°	90°	150°
N = 3	0.06±0.03	0.09±0.05	0.11±0.07	0.06±0.04	0.14±0.11	0.21±0.13	0.42±0.20	0.39±0.21	0.40±0.18
N = 5	0.08±0.02	0.13±0.05	0.17±0.06	0.10±0.04	0.20±0.09	0.30±0.10	0.51±0.11	0.51±0.15	0.51±0.15
N = 8	0.11±0.01	0.19±0.02	0.23±0.04	0.14±0.03	0.32±0.05	0.40±0.05	0.63±0.03	0.65±0.05	0.60±0.06
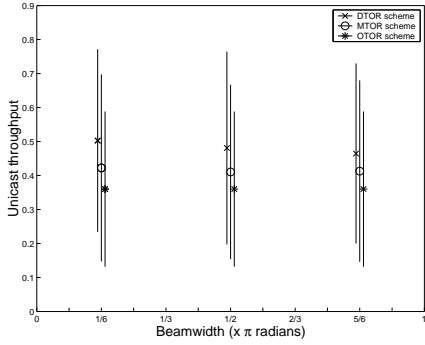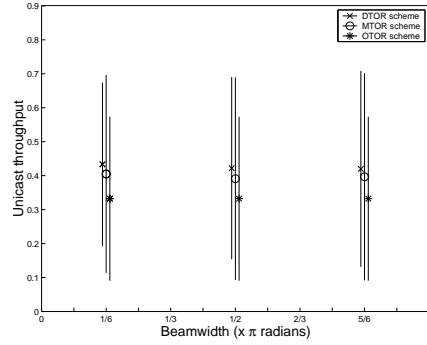
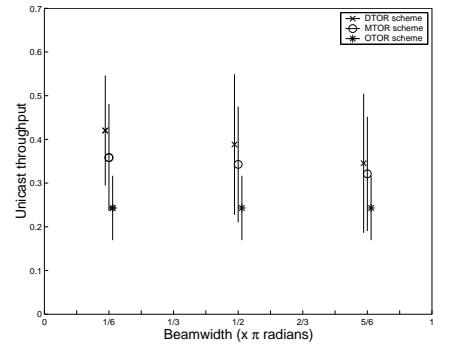(a) $r = 0.0$ (b) $r = 0.1$ (c) $r = 0.3$

Fig. 10.   Unicast throughput with broadcast traffic ($N = 3$)

(a) $r = 0.0$ (b) $r = 0.1$ (c) $r = 0.3$

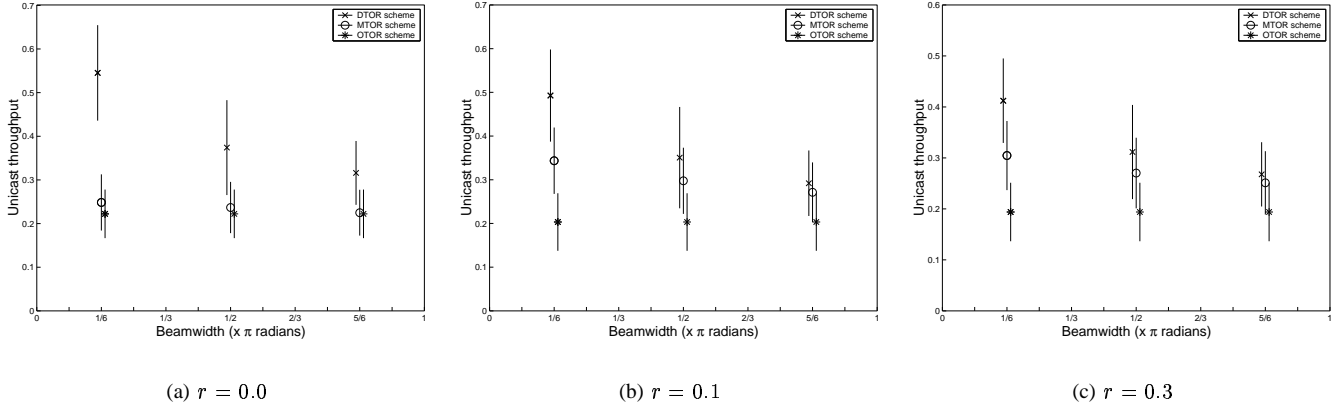Fig. 11.   Unicast throughput with broadcast traffic ($N = 5$)

(a) $r = 0.0$ (b) $r = 0.1$ (c) $r = 0.3$

Fig. 12. Unicast throughput with broadcast traffic ($N = 8$)

tiple flows may coexist at the same time. Hence the *DTDR* scheme performs the best in dense networks with larger N. When the network is less congested, the tradeoff between collision avoidance and spatial reuse is much more balanced and all schemes work similarly.

It should also be noted that the performance metrics can vary considerably even when the same uniform distribution is used throughout the simulation experiments, especially when N is small. This helps to emphasize the importance of using an analytical model and many network topologies in simulations, before meaningful conclusions can be drawn.

VI. CONCLUSION

We have presented the first analytical model of directional collision avoidance schemes that takes into account directional transmission and reception capabilities and the possibility of having different gains in omni-directional and directional transmissions. The analytical results show that the scheme in which all transmitting and receiving are done directionally can achieve much higher throughput than any other scheme that combines directional and omni-directional transmissions or receptions. The all-directional scheme maintains high spatial reuse and largely cancels the interference from hidden terminals due to imperfect collision avoidance. Furthermore, the one-hop throughput of the all-directional scheme does not degrade with the increase of competing nodes within a region, which shows that the all-directional scheme is also much more scalable in dense ad hoc networks. It is also shown that higher directional transmission gain can have negative effects on the performance of directional collision avoidance schemes due to the increased interference range and reduced spatial reuse.

Extensive simulations of the popular IEEE 802.11 MAC protocol and its directional variants validate the analytical results. The very low ratio of data packet collisions in the schemes with directional receiving confirms that directional receiving can cancel out almost all the adverse effects of hidden terminals which seem to be the throughput bottleneck even for conservative collision avoidance scheme as exemplified in the IEEE 802.11 MAC protocol.

Simulation results also show that even a large fraction of broadcast traffic (e.g., 30%) does not degrade much the performance of directional collision avoidance schemes. Together with the analytical and the rest of the simulation results, this shows that an all-directional scheme is very attractive and practical for ad hoc networks. It attains much better throughput and delay than the other schemes, and the neighbor protocol that it needs to obtain location information of neighboring nodes can be implemented using very simple methods, without degrading its performance significantly.

In practice, some form of power control to achieve similar gains for both omni-directional and directional transmissions is desirable to take full advantage of the antenna systems. It is also possible to use power control to reduce both interference and energy consumption. Interesting areas of future research include analyzing the impact of side lobes in the performance of the protocols and eliminating omni-directional transmissions and receptions altogether by means of a directional beaconing mechanism, and comparing the performance of such a scheme against schemes that rely on omni-directional beaconing.

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